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This study describes the fundamentals for the application of a Gaussian Plume Model.

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Fundamentals for the Application of a Gaussian Plume Model

A Report of the NATO/CCMS Pilot Study
on Air Pollution Assessment Methodology and Modeling

No. 102

COMMITTEE ON THE CHALLENGES OF MODERN SOCIETY
NORTH ATLANTIC TREATY ORGANIZATION
(April 1979)

Preface

The North Atlantic Treaty Organization (NATO) established the "Committee on the Challenges of Modern Society" (CCMS) at the November 1969 meeting of the North Atlantic Council.

The CCMS was charged with developing meaningful environmental and social programs that complement other international programs, and with showing leadership, first, in solution of existing problems and, second, in development of long-range goals for environmental protection in the NATO sphere of influence and in other countries as well. A first Pilot Study on Air Pollution was initiated by the CCMS at its inaugural meeting in December 1969. The United States (Environmental Protection Agency) has been the pilot nation with the Federal Republic of Germany (Federal Ministry of the Interior) and Turkey (Scientific and Technical Research Council) as copilot-nations.

The Pilot Study on Air Pollution was an action program designed to demonstrate and encourage the utilization of existing knowledge for the development of air quality management programs. It entailed the demonstration of a system approach to air quality management. Case studies have been carried out in Ankara, Turkey; Frankfurt, Federal Republic of Germany; St. Louis, U. S.; Oslo, Norway; South Holland Region, The Netherlands (NATO/CCMS Report No. 6, Appendices A - E).

The results of the pilot study are documented in NATO/CCMS Report No. 6 (Revised) "Guidelines to Assessment of Air Quality" of October 1972 and in NATO/CCMS Report No. 33 (Final Report) containing 15 recommendations as well as in several other documents, listed as Annex II to this document.

Starting from three of the above recommendations (VI, VII and XIV) the Federal Republic of Germany proposed to initiate a new Pilot Study on Air Pollution Assessment Methodology and Modeling at the CCMS Plenary Session on October 22 and 23, 1974.

These NATO/CCMS Recommendations are:

RECOMMENDATION VI

Member nations will co-operate to develop standardized methods for emissions data storage and retrieval to support requirements in the conduct of national air quality management programs. The US National Emission Data System (NEDS) might serve as a model for a common international system.

RECOMMENDATION VII

Member nations will co-operate to develop standardized techniques for projecting emissions and predicting future ambient air quality.

RECOMMENDATION XIV

Member nations agree the CCMS modeling activity has shown that there is a widespread need for further international co-operation to accomplish the following tasks:

Bring together model developers and air quality managers for exchange of ideas, discussion of users' needs and demonstration of modeling techniques.

Standardize modeling techniques for specific air quality management applications and consider how computerized models might be made available for all users.

Continue to review on-going air quality assessment studies.

In spring 1975 the North Atlantic Council approved the German proposal. The pilot study work started with the Federal Republic of Germany (Federal Ministry of the Interior) as pilot nation and the United States of America (Environmental Protection Agency) and Belgium (Service du Premier Ministre) as co-pilot nations:
A Working Group and two Panels were established with the following functions:

Assessment Methodology Panel

- Pursue and carry out Recommendations VI and VII
- Continue to review present and future assessment studies with respect to the application of assessment methodology.

Modeling Panel

- Develop standardized models for various air quality management applications.
- Develop programs to improve modeler/user communications in conjunction with the Assessment Methodology Panel and the Working Group.
- Continue as an information forum on new modeling concepts and techniques, organizing once a year international technical meetings on air pollution modeling and its application.

In addition the Working Group established an Ad-Hoc Group on Air Quality Management Systems to revise and update the NATO/CCMS Report No. 6 (Revised) 1972 by preparing a new document on "Guidelines to Air Quality Management Systems".

Another Ad-Hoc Group was set up for compiling a Glossary of Terms frequently used in assessment methodology, modeling and air quality management systems.

As an outcome of this Pilot Study on Air Pollution Assessment Methodology and Modeling the following NATO/CCMS documents are published (see also Annex III):

Air Quality Management System

- Guidelines to Air Quality Management System.

Assessment Methodology

- Air Pollution Emission Inventory Systems
- Air Pollution Emissions Projecting

Air Pollution Modeling

- Introduction to Air Quality Modeling
- Uses and Needs for Air Quality Modeling
- Bibliography on Grey Literature on Air Quality Modeling, Part I (Applied Models)
- Bibliography on Grey Literature on Air Quality Modeling, Part II (New Modeling Techniques)
- Practical Demonstration of Multiple Source Urban Air Quality Modeling (Gaussian Plume)
- Fundamentals for the Applications of a Gaussian Plume Model

Other Publications

- Glossary of Terms
- Proceedings of the 6th to 9th International Technical Meetings on Air Pollution Modeling and its Application
  (6th Meeting, 24. - 26. Sept. 1975, Frankfurt/Main, Germany)
  (7th Meeting, 7. - 10. Sept. 1976, Airlie House, USA)
  (8th Meeting, 20. - 23. Sept. 1977, Louvain-la-Neuve, Belgium)
  (9th Meeting, 29. - 31. Aug. 1978, Toronto, Canada).

The chairman of the Working Group wishes to acknowledge the scientists participating from pilot, copilot, and observer countries, and the many other persons, who assisted in the preparation of this document.

The panel, which performed diligently throughout the course of this effort, receives the highest praise. The panel members were:

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The addresses of the panel members are listed in Annex I.

Full recognition is given to each panel member for carrying out and coordinating review and other activities related to the development of this document in his respective country and to Ms. C. Morawa of the Federal Environmental Office, Germany for her effort in coordinating and organising and for editorial work.

For the Working Group,
Erich Weber, Chairman.

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1. Introduction

The purpose of this document is to give information on the capabilities, applicability and limitations of a special deterministic model to calculate ambient air pollution concentrations, the Gaussian plume model. This model utilizes emissions inventory, meteorological parameters, and equations which describe mathematically the physical process of turbulent transport of air pollutants in the lower atmosphere to calculate concentrations.

This document is addressed to those who must decide upon the model to be used in order to perform concentration calculations for applications such as plant licensing or air quality management. A comprehensive survey of model types is given in the NATO/CCMS document "Introduction to Air Quality Modeling" (see also Annex III.). A review of the variety of applications of Gaussian plume models is outlined in the NATO/CCMS document "Uses and Needs of Air Quality Models".

2. Basic Principle

2.1 The Gaussian Plume Equation

The so-called Gaussian plume equation describes mathematically how to calculate the concentration "c" of a gas or a gas-equivalent air pollutant (e. g. dust with particle sizes of less than 10 μm) being emitted from a single source continuously:

$$c(x,y,z) = \frac{Q \cdot \varkappa}{2\pi \bar{u} \cdot \sigma_y(x) \cdot \sigma_z(x)} \exp\left(-\frac{y^2}{2\sigma_y^2(x)}\right) \cdot$$

$$\left\{ \exp\left(-\frac{(z-h)^2}{2\sigma_z^2(x)}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2(x)}\right) \right\} \qquad (1)$$

where

(x,y,z) = location of receptor point given in rectangular coordinates with the origin at ground level at the source location and x-axis parallel to wind direction

Q = continuous source emission rate of the air pollutant

= parameter taking into account physical or chemical transformations

h = effective source height (equals geometric source height + plume rise)

$\bar{u}$ = mean transport (wind) speed

$\sigma_y(x)$
$\sigma_z(x)$ = diffusion parameters

This equation is an analytical solution of the simplified diffusion equation /1/

$$\bar{u} \frac{\partial c}{\partial x} = k_z \frac{\partial^2 c}{\partial z^2} + k_y \frac{\partial^2 c}{\partial y^2} \qquad (2)$$

under the assumption of Gaussian distributions of the pollutant concentration in the plume normal to the drift direction of the plume.

It is furthermore assumed (refer to NATO/CCMS document "Introduction to Air Quality Modeling):

- that the pollutant transfer by advection in the drift direction is greater than by turbulent diffusion

- that steady state conditions are prevailing which implies that all variables and parameters are constant in time
- that k_y and k_z are constant in the x, y and z directions
- that no absorption or depletion at the ground occurs; this means, that the plume can be described mathematically as completely reflected at the ground level which is assumed to be flat (last term of eq. (1)).

If calculations are to be performed at ground level (z=0) only, equation (1) reduces to

$$c(x,y,z=0) = \frac{Q \cdot \alpha}{\pi \cdot \bar{u} \cdot \sigma_y(x) \cdot \sigma_z(x)} \exp\left(-\frac{y^2}{2\,\sigma_y^2(x)}\right) \cdot \exp\left(-\frac{h^2}{2\,\sigma_z^2(x)}\right) \quad (3)$$

Vertical diffusion of a plume by turbulent mixing is limited both by the earth's surface and often by the existence of a stable layer of air aloft, i.e. an inversion layer (mixing height).

The effect of such limited mixing is described quite satisfactorily in terms of multiple reflections of the plume at the mixing height and at the ground. In this procedure each reflection is represented by a plume from an image source. The reflections can be represented mathematically by a convergent infinite series of Gaussian plume terms. Normally one or two terms are sufficient for convergence.

The ground level concentration can then be calculated by the following equation:

$$c(x,y,o) = \frac{Q \cdot \alpha}{\pi \cdot \bar{u} \cdot \sigma_y(x)\,\sigma_z(x)} \cdot \exp\left(-\frac{y^2}{2\,\sigma_y^2(x)}\right) \cdot$$

$$\sum_{n=-\infty}^{+\infty} \exp\left(-\frac{(h+2nL)^2}{2\,\sigma_z^2(x)}\right) \quad (4)$$

where L = mixing height.

2.2 Elements of the Gaussian Plume Equation

Basic Assumptions

The assumption which neglects the turbulent diffusion in the drift direction relative to advection implies that the Gaussian plume equation should usually be applied for average transport speeds of more than 1 m/s.

The use of a constant average transport speed and a fixed wind direction during the basic time period reflect the assumption of a stationary and homogeneous horizontal wind field. Directional wind shear in the boundary layer is not considered either.

The Gaussian plume equation therefore can only calculate short term concentrations over basic time periods (of about 1/2 to 1 hour) for which there are no significant changes of wind direction and speed and which can be represented by the diffusion parameters σ_y and σ_z.

The basic model does not consider the plume history, i.e. each basic time period is completely independent.

Mean Transport Speed

The mean transport speed is required as input to the Gaussian plume equation. It should be representative of the conditions throughout the vertical height interval in which the plume is dispersing. The wind speed in the lower atmosphere varies with height above ground, however. Since wind measurements are generally performed near ground level only (7 to 10 meters) an adjustment for the expected height range of dispersion has to be made. The variation of wind speed with height depends also on the atmospheric stability. Depending on the application the representative transport speed must be determined by averaging over the corresponding range of height, e. g. the expected height range of dispersion or of plume rise. For detailed methods of describing the wind profile and averaging procedures see the Appendix.

Stability of the Atmosphere

The diffusion of air pollutants in the lower atmosphere is strongly influenced by the local atmospheric stability. The more unstable the atmosphere is, the faster dispersed the plume will be.

The stability of the atmosphere can be derived from vertical and horizontal turbulence measurements or via measurements of the vertical temperature profile (gradient of temperature), of the wind speed, of the net radiation or of the cloud cover, ceiling height and solar elevation. For practical reasons an approximation has to be made wherein the continuum of possible turbulence situations in the atmosphere is described by several (4 to 7) stability classes. Some details and examples of different classifications are given in Appendix.

Diffusion Parameters

A main assumption for solving the diffusion equation is the existence of a Gaussian normal distribution of the concentration perpendicular to the transport direction. The diffusion parameters σ_y and σ_z are defined as the standard deviations of these Gaussian distributions. They are functions of the downwind distance from the emission source and of the stability of the atmosphere.

Diffusion parameters are derived either from diffusion experiments with chemically inert tracer gases or via wind fluctuation measurements. In most cases these empirical values are representative of sampling times of up to about one hour. Depending on the release height and the ground roughness the diffusion parameters vary. Normally the parameters are smaller for larger heights, for smaller ground roughnesses and for more stable atmospheric conditions. More details on different sets of diffusion parameters are outlined in the Appendix.

Effective Source Height

The concentration of air pollutants in the vicinity of a source depends strongly on the release height and the plume rise. The sum of both is often called the "effective source height". The plume rise is influenced not only by the difference in temperature between the exhaust gas and the ambient air, but also by the wind speed, the exit velocity and the stability of the atmosphere. Many attempts have been made to describe the plume behaviour immediately after it has left the source. However, there is not yet an ideal general formula available. Some plume rise formulas are given in the Appendix.

Physical or Chemical Transformations

When one solves the simplified diffusion equation (eq. (2).) it is assumed that the mass of air pollutants is conserved throughout the transport process; that means = 1 (refer to eq. (1).). However air pollutants may undergo physical or chemical transformations. Such chemical transformations may result in the loss of a pollutant due to decay or even the creation of a pollutant due to the decay of another substance. Physical transformations may be for example dry or wet deposition, adsorption or absorption. (For more details see the Appendix.)

Emission and Source Data

The Gaussian plume equation allows one to calculate the air pollutant concentration due to a single point source when the following source data are available:

- pollutant emission rate,
- time, frequency and duration of the emission,
- physical stack height,
- exhaust gas emission rate,
- exhaust gas velocity or alternatively stack gas diameter
- exhaust gas temperature.

The latter four parameters are necessary to estimate the plume rise.

2.3 Multiple Source Handling

In general, calculations of air pollutant concentrations (at ground level) have to be made for a field of many sources. Under the restriction of no interdependence of the different sources a superposition of m sources emitting the same air pollutant is described by the following - omitting an influence of the mixing height

$$c(x,y,o) = \sum_{i=1}^{m} c_i \quad (x,y,o) \qquad (5)$$

with

$$c_i(x,y,o) = \frac{Q_i \exp\left(-\frac{(y-y_i)^2}{2\sigma_y^2(x-x_i)}\right) \cdot \exp\left(-\frac{h_i^2}{2\sigma_z^2(x-x_i)}\right)}{\pi \cdot \bar{u}_i \cdot \sigma_y(x-x_i) \cdot \sigma_z(x-x_i)}$$

where

- i refers to the i-th source of the multiple source field
- x -axis corresponds to the main transport direction
- $(x-x_i)$, $(y-y_i)$ are the relative coordinates of the receptor point with respect to the i-th source
- h_i is the effective source height of the i-th source and
- $\bar{u}_i$ is the mean transport speed with respect to the diffusion from the i-th source.

A complex field of many sources normally includes point, line and area sources. Stacks and other well defined single outlets are generally handled as point sources. Plume rise calculations can be performed for these type of sources. Diffuse sources like leakages, tank farms or domestic heating may be defined as area sources while streets are line sources.

Line or area sources do not usually have significant effluent exit velocities or temperatures so that a plume rise estimation need not be necessary in general. Methods exist whereby such line or area sources may be represented by point sources and thus handled by the Gaussian plume equation. Some methods of simulating line or area sources are reviewed in Appendix.

3. Applicability

3.1 Problems due to Assumptions

The Gaussian-plume formula is representative only of flat terrain, steady state conditions and a homogeneous atmosphere. These conditions translate into the following source, meteorological and topographic factors:

- Continuous uniform emission rate; in the case of short term (duration of some minutes) or noncontinuous emission rates a transformation from the value derived by assuming a 1/2 or 1 hourly constant emission has to be performed or a different formula should be used.

- Homogeneous horizontal wind field; uneven terrain such as hills and valleys influence the wind direction and thus a correction with respect to drift direction must be made if the Gaussian plume equation is to be applied.

- Representative hourly mean wind; concentration calculations require that meteorological conditions be representative for a time base of about 1/2 to 1 hour. Wind direction often exhibits meander during this time period, however, so this effect must be taken into account.

- Directional wind shear in the vertical; the increase of wind speed with height can be taken into account to a certain extent (ref. Appendix). However, a wind directional variation with height normally cannot be considered when using the Gaussian plume equation.

- Constant eddy diffusivities; the dispersion coefficients are assumed constant with height for a certain release height and with crosswind distance. A corresponding height dependence ought to be considered. However, dispersion parameters derived from field experiments have to be used in the form of height- and crosswind-averaged values for the release height of the experiment.

3.2 Limitations

Due to the assumptions of atmospheric homogenity and stationarity the Gaussian plume equation should only be applied over those distances for which the aforementioned assumptions could be expected to reasonably hold.

The Gaussian plume formula should also be used only for downwind distances for which the dispersion parameters have been determined experimentally (e. g. via tracer experiments) or semi-empirically (e. g. via wind fluctuation measurements). The use of dispersion parameters extrapolated to distances of more than some ten kilometers or of less than about 100 m can only show the tendency of the concentration values to be expected.

Calm wind situations (wind speed of about 1 m/s or less) cannot be handled by the Gaussian plume equation because at such low wind speeds the turbulent diffusion is equivalent to or even supersedes the advection influence.

No deposition nor depletion at the ground could be taken into account without violation of the Gaussian hypothesis. No chemical reactions are allowed in such a model. However, an exponential correction factor for a half-life time could be introduced.

Dispersion is influenced by the physical structure of the building complexes. For example, large objects can produce aerodynamic down-wash, causing higher concentrations in their immediate vicinity. Additional assumptions then have to be made before using the Gaussian plume formula.

Heat islands generated by plants may cause additional plume rise or influence the dispersion processes and these effects are normally not included in experimentally determined dispersion parameters.

Uneven terrain like terrain steps, influences the air flow and therefore the strictly horizontal transport of pollutants, as assumed in the Gaussian plume equation, is unrealistic under such conditions. Corresponding corrections must be performed if this model is to be applied.

3.3 Validation and Calibration

The applicability of a model in general - and so also of the Gaussian plume model - depends on its accuracy. Therefore the model results should be compared to measurements whenever possible. If the spatial structure of model results

and measurements are similar and the concentrations differ in magnitude only, a calibration may be performed in order to fit the calculations to the measurements. Such a calibration should, however, be performed only when representative measurements - with respect to time and space - are available. This allows a validation of the model. A model may be considered to be validated if the calculated and measured values do not differ (1) in the annual averages by more than approximately 30 % and (2) short term concentrations (e. g. 95 percent values of the cummulative frequency distribution) by a factor of approx. 2.

A model will fit measured data best when consistent sets of dispersion parameters, turbulence classes and plume rise formulas are used.

4. How to Apply the Gaussian Plume Model

4.1 General

The aim of applying the Gaussian plume equation is to calculate the air quality at certain receptor points. The air quality or the air pollution load can be described very roughly by the concentration of air pollutants averaged over time or space or both. A more detailed description is accomplished by giving the cumulative frequency distribution of concentrations being exceeded during certain times (hours of a year) for different representative receptor points or areas. Frequency distributions of this type can be determined by repetitively applying the Gaussian plume equation for all possible meteorological situations characterized by wind direction, wind speed and turbulence conditions of the atmosphere. Combining the calculated concentration values with the frequencies of the joint occurrence of the corresponding meteorological data the frequency distribution or the cumulative frequency distribution is determined.

In practical cases the emissions are not constant, i. e. sources may be active for several hours per day. The joint frequency distribution of the meteorological data, however, represents the whole year (8760 hours). In such cases a superposition of the probability of the combination of meteorological data and the probability of the emission status can be performed to determine the frequency distribution of concentrations and thus the air quality.

4.2 Check List of Necessary Data

The ability to perform diffusion calculations depends on the availability of appropriate input data, representative dispersion parameters and sufficient meteorological information relevant to the diffusion process. The following check list gives a survey of the data necessary to perform calculations:

Emission and source data:

- air pollutant to be investigated
- source location, i.e. geographical coordinates
- source dimensions, i.e. height and exit diameter
- mass flow rate of air pollutant from the source
- volumetric flow rate of the total exhaust gas from the source
- exhaust gas exit temperature
- time dependence of pollutant emission rate, i.e. duration, frequency as well as diurnal and seasonal dependence if applicable

Transport and dispersion (meteorological) data:

- average wind direction, for time periods of 1/2 or 1 hour
- average wind speed or, preferable, wind speed variation with height
- description of turbulent structure of the atmosphere, e. g. atmospheric stability
- mixing height, e. g. height of inversion layer
- air temperature (for plume rise calculations)
- joint frequency distribution of at least the first three meteorological parameters
- vertical and horizontal dispersion parameters representative of characteristic turbulence situations

Data derived from emission and meteorological information which require a particular method or formula for their calculation:

- averaged transport speeds representative of the total layer in which dispersion takes place and of the range of plume rise,
- plume rise estimate.

Data for the receptor points

- geographical location of the area or the defined receptor points where the air pollution load is to be calculated, i.e. geographical coordinates and height above ground (geometric and/or geodetic height)

- grid size for receptor points in order to be representative of a whole area.

4.3 Availability of Data and Related Problems

The emission and source data will be available for the sources and air pollutants under consideration if a comprehensive emissions inventory is performed (refer to NATO/CCMS document "Emissions Inventory"). Depending on the degree of detail in the emissions inventory, more or less precise information can be extracted on the time dependence of the emissions. In principle all data should be available.

A lot of the meteorological data can be supplied by the national weather services. Very often, however, wind data are only available as instantaneous values. The Gaussian plume model, on the other hand, needs time-averaged values as well as the joint frequency distributions of wind speed, direction and turbulence. In cases where frequent limited mixing is expected the corresponding information (e. g. height of the inversion layer) is required but is seldom available in sufficient detail.

A great problem will arise when decisions have to be made concerning the selection of diffusion parameters, plume rise formulas or parameters to be introduced into wind speed averaging methods. An approach to this problem is discussed in the following.

Though there are many sets of diffusion parameters published one best set cannot be recommended. The following criteria are provided therefore to support a decision on the most representative set of diffusion parameters for a specific problem.

Select the parameter set that has been determined experimentally

- in a terrain that is as equivalent to the terrain under investigation as possible
- within a source-receptor distance range equivalent to the actual range of source receptor distance
- at a source whose height is closest to that of the source under consideration
- at a source with emission characteristics (mainly exhaust gas temperature) similar to the source to be investigated.

Therefore:

- A set of dispersion parameters determined at a "cold source" should not be used for a "hot source" of the same height or higher.
- Parameter sets determined over very flat terrain with very little roughness should not be used for sources in urban or strongly industrialized regions.
- The extrapolation of parameter sets far outside of the distance range over which they were measured should not be done.

Many plume rise formulas have been published in the past. However, it cannot be uniquely decided which one is the best and the choice depends on the particular application as well as one's experience with the different formulas. For example, a plume rise formula that tends to underestimate the real plume rise may be used for calculations during licensing procedures where a safety margin should be allowed. A plume rise formula that describes best the

mean real plume rise but with a larger scatter (uncertainty) may be used during applications of the model e. g. for cause analysis. The most accurate description of the plume rise takes the turbulent state of the atmosphere into account.

Since the vertical profile of wind speed is not generally available, methods have to be used to extrapolate the wind speed measured near the ground to larger heights and then to average over an appropriate height range. There are formulas available to estimate the wind speed at greater heights under different turbulence situations though it is known that each turbulence situation can exhibit great variability in the wind profile.

With respect to the receptor points, proper attention should be given to selecting defined receptor points so as to be representative of the area under consideration or to choose a narrow enough grid to reflect the structure of the air pollution load in a whole area as well as possible and necessary.

Appendix

A.1. Mean Transport Speed

The wind speed is measured in general near ground level (about 10 m above ground) only. An assumed dependence on height must therefore be taken into account for concentration calculations. Extensive measurements of this height dependence have been performed in research programs (e. g. /A 1/) the results of which are as follows:

The height dependence of the wind speed is often described in the literature by a power law:

$$\bar{u}\ (z) = \bar{u}\ (z_o)\ \left(\frac{z}{z_o}\right)^m$$

with
- z = height above ground
- z_o = reference height above ground
- $\bar{u}$ = time averaged wind speed
- m = wind profile exponent

For detailed calculations it is mostly set

$$\bar{u}\ (z < z_o) = u\ (z_o)$$

The mean transport speed representative of an appropriate height range, e. g. from the effective source height (h) to ground level (for dispersion calculations) or from physical (H) to the effective source height (for plume rise calculations) may then be calculated via integration:

$$\bar{u} = \frac{1}{\Delta z} \int \bar{u}\ (z)\ dz = \frac{1}{(z_2 - z_1)} \int_{z_1}^{z_2} \bar{u}\ (z_o)\ .\ \left(\frac{z}{z_o}\right)^m dz$$

where $z_1 = 0$ or H
$z_2 = h$

The relationship then finally reads:

$$\bar{u} = \frac{\bar{u}\ (z_o)}{m + 1} \cdot \frac{(z_2^{m+1} - z_1^{m+1})}{z_o^m \cdot (z_2 - z_1)}$$

For $z_1 = 0$ and $z_2 = h$: $\bar{u} = \frac{\bar{u}\ (z_o)}{m + 1} \left(\frac{h}{z_o}\right)^m$.

Wind profile exponents for different turbulent situations have been published /A 2, A 3, A 4, A 5/ For example those of Manier /A 2/ are as follows, according to Klug's stability classification /A 6/:

turbulence situation/class		m
extremely stable	I	0,419
stable	II	0,369
neutral	III_1	0,282
slightly unstable	III_2	0,223
unstable	IV	0,205
extremely unstable	V	0,089

A.2. Stability of the Atmosphere

The continuum of turbulence states of the atmosphere must be described by discrete stability classes in order to be handled practically. Different turbulence classification schemes have been developed by several authors /A 1, A 6 - A 9/; some of them may be mentioned here:

- Pasquill /A 7/

  The relationship of turbulence types to weather conditions are defined as follows:

A = extremely unstable
B = moderately unstable
C = slightly unstable
D = neutral
E = slightly stable
F = moderately stable

The meteorological data which are used to determine the turbulence type are the surface wind speed, the daytime insolation and the nighttime cloudiness. A description of this classification scheme is given in /A 3/.

- Turner /A 8/

The following classes represent the specified turbulence conditions:

1 = extremely unstable
2 = unstable
3 = slightly unstable
4 = neutral
5 = slightly stable
6 = stable
7 = extremely stable

These stability classes are functions of wind speed and net radiation. A detailed description is given in /A 8/.

- Klug /A 6/

The turbulence conditions are classified as follows:

I = extremely stable
II = stable
III_1 = neutral to slightly stable
III_2 = neutral to slightly unstable
IV = unstable
V = extremely unstable

The scheme is similar to that of Pasquill. It is more objective, however since it takes into account the total cloud cover and further additions and modifications as outlined in detail in /A 6/.

- Klug and Manier /A 1/

This scheme is similar to that of Klug except that some further modifications are introduced. These relate mainly to accounting for the time relative to sunrise and sunset.

The aforementioned classification schemes can be employed on the basis of regular meteorological observations.

The following classification of

- Polster /A 9/

takes into account temperature fluctuation data which normally are not available at standard meteorological stations (e. g. synoptical stations at airports).

The turbulence situations are classified as follows:

A = extremely unstable
B = moderately unstable
C = slightly unstable
D, D^+ = neutral
E = slightly stable
F, G = extremely stable

Details on this scheme are outlined in /A 9/.

A.3. Diffusion Parameters

The dispersion of air pollutants in the atmosphere takes place under the influence of turbulent diffusion. The standard deviations or diffusion parameters of the Gaussian plume equation can be determined by tracer experiments /A 6, A 10 - A 16/ or measurements of the wind fluctuation /A 5, A 17 - A 21/.

The most appropriate set of diffusion parameters should be selected on the basis of the particular application. The following list is not complete but gives the sets of parameters used most often.

In most cases the diffusion parameters can be described by

$$\sigma_y (x) = F \cdot x^f \quad \text{and} \quad \sigma_z (x) = G \cdot x^g$$

- Pasquill /A 7/

These diffusion parameters classified into six turbulence categories are based on tracer experiments (Prairie Grass Test Series /A 11/) and on wind direction fluctuation measurements. The parameters are applicable to short-time emissions near ground level over terrain with an extremely low surface roughness. The source height of the Prairie Grass Tests was 0,5 m and the distances of receptors from

the source were less than 1 km. In spite of this fact the Pasquill diffusion parameters were applied up to 100 km. Pasquill's curves can be approximated by

$$\sigma_y (x) = (a_1 \cdot \ln x + a_2) \cdot x \qquad \text{and}$$

$$\sigma_z (x) = 0{,}465 \cdot \exp (b_1 + b_2 \ln x + b_3 \ln^2 x)$$

The coefficients are listed as follows with respect to the turbulence classification after Pasquill /A 7/:

Diffusion Category	A	B	C	D	E	F
a_1	-0,023	-0,015	-0,012	-0,006	-0,006	-0,003
a_2	0,350	0,248	0,175	0,108	0,088	0,054
b_1	0,880	-0,985	-1,186	-1,350	-3,880	-3,800
b_2	-0,152	0,820	0,850	0,793	1,255	1,419
b_3	0,147	0,017	0,005	0,002	-0,042	-0,055

- Klug /A 6/

A reevaluation of U.S. tracer experiments led to another set of diffusion parameters. This set is suited for applications to short-term concentrations from ground level sources over a terrain with low surface roughness. Source receptor distances should not exceed 2 to 3 km. These parameters are specified according to the turbulence classification of Klug /A 6/:

Diffusion Category	V	IV	III_2	III_1	II	I
F	0,469	0,306	0,230	0,219	0,237	0,273
f	0,903	0,885	0,855	0,764	0,691	0,594
G	0,017	0,072	0,076	0,140	0,217	0,262
g	1,780	1,021	0,879	0,727	0,610	0,500

- Singer and Smith (Brookhaven) /A 13/

The diffusion parameters are classified within 4 turbulence categories. The emission source was 108 m above ground at an off-shore site. The parameters may be used for applications in terrain of medium roughness, emission periods of up to 1 hour and distances up to some 10 km. The coefficients correspond to turbulence classes of Turner /A 8/:

Diffusion Category	2	3	4	5
F	0,400	0,360	0,320	0,310
f	0,910	0,860	0,780	0,710
G	0,411	0,326	0,223	0,062
g	0,907	0,859	0,776	0,709

- Mc Elroy and Pooler (St. Louis) /A 14/

These diffusion parameters were extracted from tracer test series with source heights near ground. The diffusion parameters were evaluated for distances up to 16 km. Only four turbulence classes were identified as no extremely high or low wind speeds occurred. The parameters apply for urban and equivalent areas with large surface roughness.

The coefficients correspond to Turner's stability classification /A 8/ and are as follows:

Diffusion Category	2	3	4	5
F	1,700	1,440	0,910	1,020
f	0,717	0,710	0,729	0,648
G	0,079	0,131	0,910	1,930
g	1,200	1,046	0,702	0,465

- Vogt /A 15/

Diffusion parameter sets were evaluated from tracer experiments at different heights (50 and 100 m) over a terrain with large surface roughness. The test area included distances between source and receptors of up to 11 km. The parameters can be described by a power law also and the coefficient are as follows where the turbulence classification is performed after Klug and Manier /A 1/ or Pasquill /A 7/ or Polster /A 9/:

Diffusion Category		A(V)	B(IV)	C(III_2)	D(III_1)	E(II)	F(I)
(50 m)	F	(0,868)	0,868	0,718	0,625	1,691	5,382
	f	(0,810)	0,810	0,784	0,767	0,621	0,578
	G	(0,222)	0,222	0,215	0,205	0,162	0,396
	g	(0,968)	0,968	0,944	0,936	0,809	0,618

Diffusion Category		A(V)	B(IV)	C(III_2)	D(III_1)	E(II)	F(I)
(100 m)	F	0,229	0,227	0,224	0,222	(1,691)	(5,382)
	f	1,003	0,970	0,938	0,905	(0,621)	(0,578)
	G	0,096	0,155	0,247	0,398	(0,162)	(0,396)
	g	1,158	1,024	0,890	0,755	(0,809)	(0,618)

Due to only very few experiments the 50 m source coefficients for diffusion category A were set equal to those of category B and the parameters of the 100 m source for category E and F were taken from those of the 50 m source experiment.

- Nester /A 16/

These sets of diffusion parameters were determined from tracer experiments over terrain of equivalent roughness to that of Vogt's tracer tests. No significant differences were found for different release heights of 60 and 100 m and of 160 and 195 m. The distances between source and receptors were up to 8 km.

The corresponding coefficient of the power law dependencies of the diffusion parameters are as follows where the turbulence classification is described after Klug and Manier /A 1/ or Pasquill /A 7/:

Diff.	Category	A(V)	B(IV)	C(III_2)	D(III_1)	E(II)	F(I)
	F	0,65	0,65	2,48	2,06	2,06	2,06
(60/	f	0,89	0,89	0,61	0,61	0,61	0,61
100 m)	G	0,039	0,020	0,052	0,10	0,66	1,30
	g	1,42	1,38	1,15	1,01	0,61	0,45
	F	1,21	0,61	0,30	0,27	0,30	0,30
(160/	f	0,87	0,87	0,87	0,87	0,87	0,87
195 m)	G	0,034	0,036	0,12	0,35	0,56	0,46
	g	1,50	1,30	0,98	0,71	0,55	0,50

- Bultynck /A 21/

The diffusion parameters were evaluated from tracer experiments performed from a release height of 69 m at receptor distances up to 5 km from the source.

The coefficients of the power law dependencies of the diffusion parameters are following a turbulence classification similar to Turner's /A 8/:

Diff. Category	1	2	3	4	5	6	7
F	0,235	0,297	0,418	0,586	0,826	0,946	1,043
f	0,796	0,796	0,796	0,796	0,796	0,796	0,698
G	0,311	0,382	0,520	0,700	0,950	1,321	0,819
g	0,711	0,711	0,711	0,711	0,711	0,711	0,669

- Reuter /A 22/

The diffusion parameters derived from meteorological data as e. g. wind fluctuations are written as follows:

$$\sigma_y = B \cdot t^b \quad \text{and} \quad \sigma_z = A \cdot t^a$$

where $x = t \cdot \bar{u}$ and the coefficients are according to a modified Turner classification (see /A 22/):

Diff. Category	2	3	4	5	6	7
B	1,27	1,11	1,07	0,94	0,50	0,46
b	0,90	0,87	0,84	0,80	0,80	0,73
A	0,09	0,83	0,90	0,64	0,74	0,32
a	1,46	0,89	0,76	0,70	0,57	0,50

A.4. Effective Source Height

In general the exhaust gases of sources undergo plume rise due to thermal and initial momentum influences. Comprehensive lists of plume rise formulas are given by Moses and Kraimer /A 23/ and Stern /A 24/. Several formulas are mentioned and discussed here in terms of their dependence upon atmospheric stability, initial gas velocity and/or heat emission rate.

The most commonly used formulas are those of

- Briggs /A 25, A 26/

  The formulas include a plume rise dependence with distance from the source. They are based on the heat emission rate and are differentiated for unstable, neutral and stable conditions of the atmosphere. They do not take into account an influence of the exit speed of the exhaust gases. The formula given in /A 26/ is used in the Dutch recommendations for dispersion calculations and will possibly be introduced in the German regulations.

- Moses and Carson /A 27/

  The plume rise here depends on heat emission rate and exit speed. Different formulas are given for stable, neutral and unstable conditions. The formula for neutral conditions is used in a regulation for the licensing of chemical plants in one German State (Land).

- Holland /A 28/

  This formula takes into account heat emission rate and exit speed of the exhaust gas as well. There is no distinction between different turbulence conditions and no distance dependency.

- Stümke /A 29/ /A 30/

  These formulas are based on the Holland formula which was modified for use in the German regulation on the determination of necessary stack heights. It takes into account heat emission rate and exit speed but contains no dependence on stability or on source distance.

- Concawe /A 31/

  These two formulas take account of heat emission rates but not of exit speed, or dependence on stability and source distance.

- ASME /A 32/

  Three different formulas are given for neutral and unstable conditions, for stable conditions and for momentum sources. The former two formulas include heat emission rates and the latter one the exit speed only. They show no source distance dependence.

- TVA /A 33, A 34/

  These two formulas include heat emission rates and source distance dependences but do not take into account exit speeds or stability conditions of the atmosphere.

A comparison study by Guldberg /A 35/ showed good agreement by the Briggs formulas for plume rise calculations during low wind speed situations. At higher wind speeds the TVA formulas performed best. Although, a general recommendation for the "best plume rise formula" cannot be given, decision making will be aided by the evaluations performed by Moses and Kraimer /A 23/.

A.5. Chemical and Physical Transformations

Air pollutants may undergo physical or chemical changes during their passage through the atmosphere. This can result in species depletion or creation throughout processes

as precipitation scavenging, adsorption, chemical transformation etc.

A relatively easy method is the assumption of a decay (or creation) which is proportional to the concentration of the air pollutant:

$$-\frac{dc}{dt} = \alpha_1 \cdot c$$

α_1 = constant of proportionality
c = concentration of air pollutant
t = time

This equation can be solved:

$$c(t) = c(t=0) \cdot e^{-\alpha_1 \cdot t}$$

Using the nomenclature of eq. (1) α is to be replaced by $e^{-\alpha_1 \cdot t}$, whereby α_1 stands for the reverse of a "decay time". In general such decay time must be of the order of less than 1/2 hour to be significant with respect to reducing or creating air pollutants during their transport to the receptors. Due to a lack of detailed knowledge of such decay times most calculations cannot take this effect into account. It is of great importance, however, for such calculations as that of the impact of fluorine or the nitrogen oxides NO and NO_2. The latter substances are transformed one to another depending on several influences such as solar radiation, hydrocarbon presence, temperature etc.

A.6. Line and Area Sources

Very often not only point sources must be handled by diffusion models. Line and area sources also can be treated

by various methods. Some of these are described in /A 36 - A 40/ or as follows:

- Virtual point source

  The line or area source may be described by a virtual point source placed upwind of the line or area source. The dispersion due to the virtual point source concentration at the real source location then corresponds to the actual line or area source emission distribution when the diffusion parameters σ_y is replaced by $\sqrt{\sigma_y^2 + \sigma_{yo}^2}$. Deviations of some 50 % may occur if the receptor-source distance is comparable with the source dimension /A 39/.

- Several or many point sources

  Line or area sources may be simulated by a series of point sources separated by distances d_o of some ten to some hundred meters. This value d_o depends on the distance x of the receptor point from the source: a realistic condition is $d_o \leq 0{,}2 \cdot x$ in order to be sufficiently accurate with respect to an "exact" solution.

  Empirical formulas based on the exact solution for many point sources simulating an area source were developed by Kretzschmar et al. /A 40/

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ANNEX I

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ANNEX II

NATO/CCMS Documents on the First Air Pollution Pilot Study (available at: NATO/Committee on the Challenges of Modern Society, NATO Headquarters, Brussels, Belgium)

AIR POLLUTION (No. 5)

Proceedings of the 2nd Meeting of the Expert Panel on Air Pollution Modeling, (26 - 27 July 1971, Paris, France). Out of stock

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Guidelines to Assessment of Air Quality (Revised)

APPENDIX A	Assessment of Air Quality in Ankara (February 1973)
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AIR POLLUTION (No. 67)

Third Follow-up Report (November 1977)

AIR POLLUTION (No. 96)

Fourth Follow-up Report (October 1978)

AIR POLLUTION (No. 6, Appendix C revised)

Assessment of Air Quality in Frankfurt (December 1977)

ANNEX III

NATO/CCMS Documents on the Pilot Study on Air Pollution Assessment Methodology and Modeling
(available at: NATO/Committee on the Challenges of Modern Society, NATO Headquarters, Brussels, Belgium)

Air Pollution (No. 42)

Proceedings of the 6th International Technical Meeting on Air Pollution Modeling and its Application
(24 - 26 September 1975, Frankfurt/Main, Germany)

Air Pollution (No. 51)

Proceedings of the 7th International Technical Meeting on Air Pollution Modeling and its Application
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